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DYNAMICAL CLIMATE REANALYSIS

HURRICANE DESTRUCTIVE POTENTIAL

AEROSOLS IN ARCTIC CLIMATE



GLORY

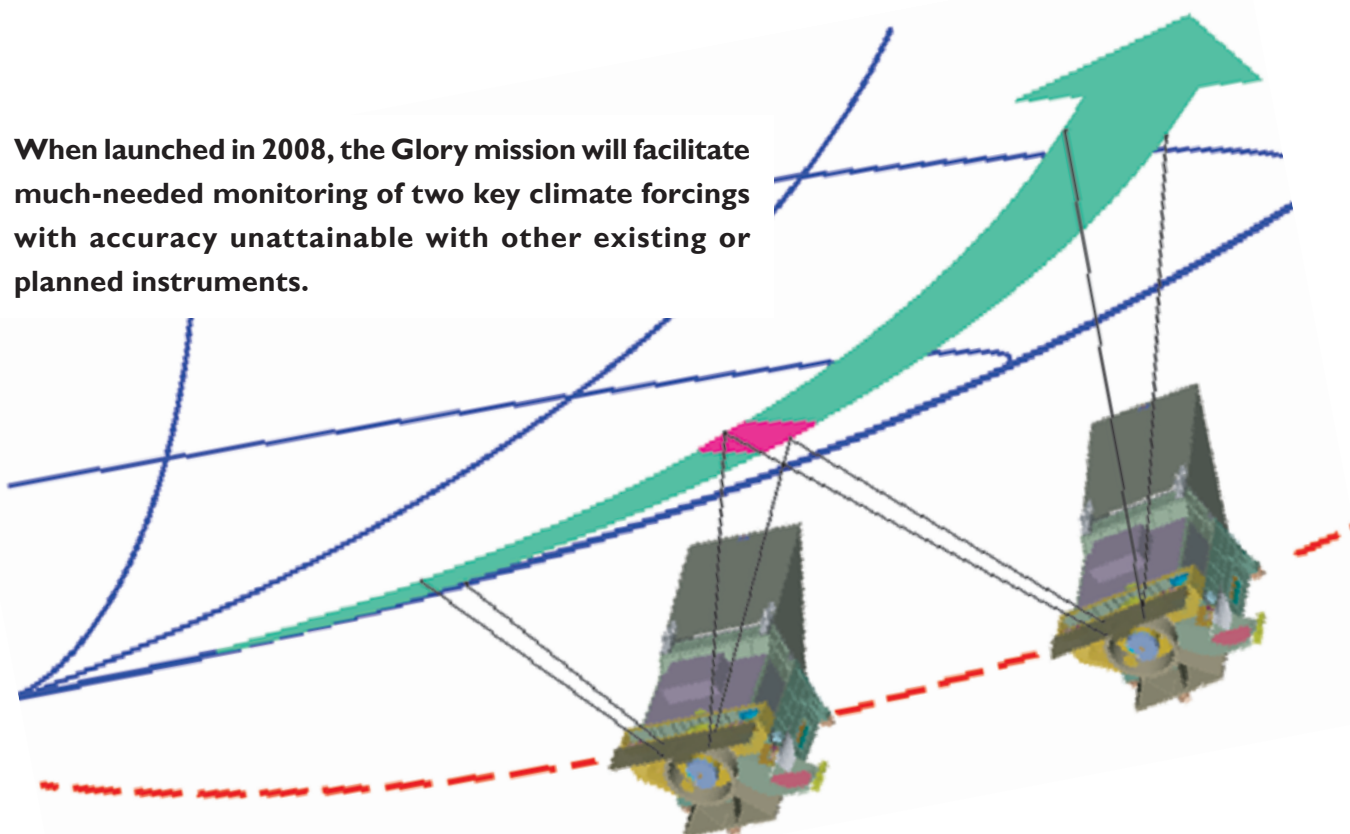
MONITORING AEROSOLS
AND SOLAR IRRADIANCE

Accurate Monitoring of Terrestrial Aerosols and Total Solar Irradiance

Introducing the Glory Mission

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When launched in 2008, the Glory mission will facilitate much-needed monitoring of two key climate forcings with accuracy unattainable with other existing or planned instruments.



APS measurements via 360° scanning from the Glory spacecraft. See Figure 8 on page 684 for more information.

The Earth's climate depends upon the balance between incident solar radiation and the response of the atmosphere and surface via absorption, reflection, and reradiation. Long-term changes in either the solar irradiance or the composition of the atmosphere can cause global climate change and thereby affect local weather patterns impacting the quality of human life.

Solar irradiance is a purely natural phenomenon, while the composition of the atmosphere is influenced by both natural and anthropogenic effects, such as the by-products of modern industrial societies. Over the past century the average temperature at the Earth's surface has increased by ►

approximately 0.7°C (Hansen et al. 2006). Accurately attributing this increase and the concomitant climate change to either natural events or anthropogenic sources (or both) is of primary importance to the establishment of scientifically and economically effective policy (e.g., Hansen et al. 2005). Clearly, the more we find these changes are due to anthropogenic sources, the more impact the results might have on policy.

Total solar irradiance (TSI) is the dominant driver of global climate, whereas both natural and anthropogenic aerosols are climatically important constituents of the atmosphere also affecting global temperature. Although the climate effects of solar variability and aerosols are believed to be nearly comparable to those of the greenhouse gases (GHGs; such as carbon dioxide and methane), they remain poorly quantified and may represent the largest uncertainty regarding climate change.

The GHG, TSI, and aerosol effects are exemplified by Fig. 1 based on a recent study by Hansen et al.

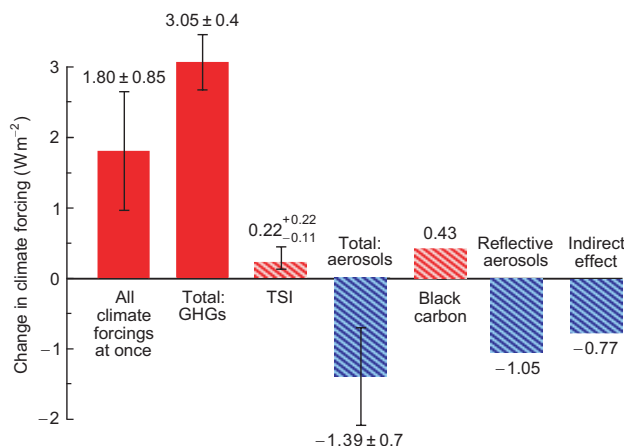


FIG. 1. Estimated changes in climate forcings during the period of 1880–2003. A positive change means a contribution toward climate warming; a negative change means a contribution toward climate cooling. The crosshatched bars represent forcings addressed by Glory.

(2005). In their analysis, the TSI forcing was estimated to be $\sim 0.2 \text{ W m}^{-2}$, with an uncertainty of about a factor of 2. The positive sign of the TSI forcing means that it contributes to global warming. The radiative forcing resulting from black carbon aerosols, via absorption of the solar energy followed by reradiation of the absorbed energy at infrared wavelengths, is also positive. Nonabsorbing aerosols such as sulfates reflect the sun's radiation back to space and typically cause cooling. In addition to these direct interactions of aerosols with radiation, aerosols are also believed to cause an indirect cooling effect by modifying cloud radiative properties and modulating precipitation. As is evident from Fig. 1, the estimated magnitude of the net aerosol forcing and its current uncertainty are comparable to those of the sum of all climate forcings.

The analysis by Hansen et al. (2005), as well as other recent studies (see, e.g., the reviews by Ramaswamy et al. 2001; Kopp et al. 2005b; Lean et al. 2005; Loeb and Manalo-Smith 2005; Lohmann and Feichter 2005; Pilewskie et al. 2005; Bates et al. 2006; Penner et al. 2006), indicates that the current uncertainties in the TSI and aerosol forcings are so large that they preclude meaningful climate model evaluation by comparison with observed global temperature change. These uncertainties must be reduced significantly for uncertainty in climate sensitivity to be adequately constrained (Schwartz 2004). Helping to address this challenging objective is the main purpose of the National Aeronautics and Space Administration (NASA) Glory mission, a remote sensing Earth-orbiting observatory designed to support the U.S. Climate Change Science Program, which is scheduled for launch in December 2008 as part of the A-Train constellation of Earth-orbiting satellites (Fig. 2). Specifically, Glory is intended to meet the four following scientific objectives:

- improve the quantification of the effect of solar variability on the Earth's climate by continuing the uninterrupted 28-yr satellite measurement record of TSI;

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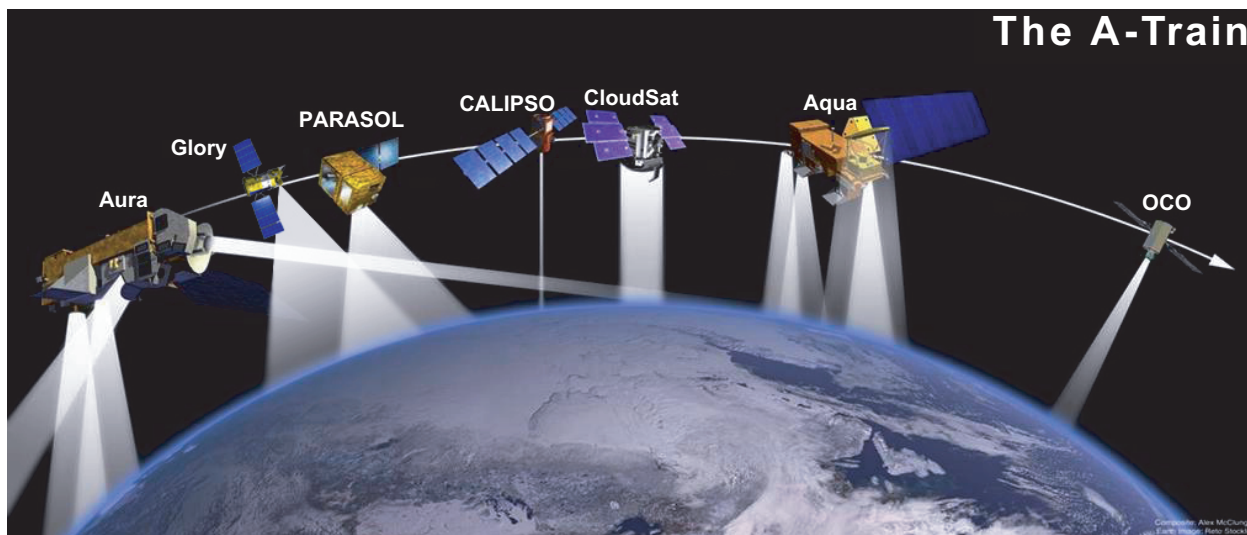


FIG. 2. The A-Train constellation and its members: the Earth-Observing System *Aqua* and *Aura* platforms, the *Glory* spacecraft, the Polarization and Anisotropy of Reflectances for Atmospheric Sciences coupled with Observations from a Lidar (PARASOL) satellite, the CALIPSO satellite, the CloudSat, and the Orbiting Carbon Observatory (OCO).

- facilitate the quantification of the aerosol direct and indirect effects on climate by determining the global distribution of the optical thickness and microphysical properties of natural and anthropogenic aerosols and clouds with much-improved accuracy;
- provide better aerosol representations for use in various remote sensing retrievals, thereby allowing improvements in aerosol assessments by other operational satellite instruments; and
- provide an improved framework for the formulation of future comprehensive satellite missions for aerosol, cloud, and ocean color research.

These science objectives will be met by implementing two independent instruments. The Total Irradiance Monitor (TIM) will monitor sunlight incident on the Earth's atmosphere by performing measurements of TSI with extremely high accuracy and precision. The Aerosol Polarimetry Sensor (APS) will have the ability to collect accurate multiangle photopolarimetric measurements of the Earth along the satellite ground track over a broad visible and near-infrared spectral range, thereby providing aerosol retrievals to levels of precision and accuracy heretofor unachievable. The main purpose of this paper is to explain the scientific rationale of the *Glory* mission, discuss how the scientific objectives dictate the specific measurement strategy, and describe how the measurement strategy will be implemented by building and flying two state-of-the-art satellite instruments.

TOTAL IRRADIANCE MONITOR. Spaceborne TSI measurements began in 1978 and quickly dispelled the misconception that the solar irradiance was constant (Willson et al. 1981; Willson and Hudson 1991; see Fig. 3). Correlations between the current 28-yr record of continuous TSI measurements and indicators of solar activity, such as sunspots and cosmogenic isotopes, have provided estimates of historical effects of the solar influences on the Earth's climate (Lean et al. 1995; Pang and Yau 2002). Indications that the sun has been more active in the last 60 yr than it was during the prior 1000 yr (Usoskin et al. 2003) provide strong motivation for the precise monitoring of the present-day sun to discriminate natural from anthropogenic climate forcings both now and in the future.

While several signatures of solar variability are seen in terrestrial records across broad time scales (Reid 1999; Crowley 2000; Bond et al. 2001; L. Hood 2002, unpublished manuscript), the modeled sensitivity of the Earth's climate to variations in TSI has a large uncertainty because of poorly understood coupling with climate feedback systems (Rind 2002). Such estimates of sensitivity to solar forcing are based on correlations between long-term proxies of both TSI and terrestrial temperatures, which in turn are based on recent measurements. Because the extension of these records spans thousands of years back in time, the current measurements on which they are based must be extremely accurate. Currently, there are discrepancies in reconstructions of a TSI composite at the level of 40 ppm yr⁻¹ using data from the existing TSI

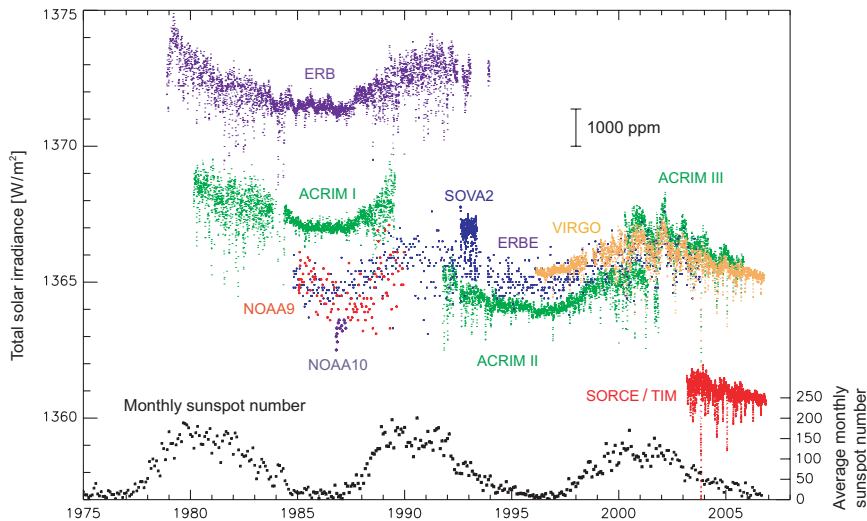


FIG. 3. The spaceborne TSI record is due to several instruments, which fortunately have sufficient overlap to provide continuity despite the relatively large differences between each instrument on an absolute scale. Correlations with sunspot number provide a proxy to extend TSI estimates back 400 yr.

record (Willson and Mordvinov 2003; Fröhlich 2007), so future measurement stability is also critical.

To achieve the desired measurements of both high accuracy and stability, the TIM instrument is intended to have an absolute accuracy level of 100 ppm and a stability known to 10 ppm yr⁻¹. This level of accuracy helps to maintain a connection to the currently uninterrupted 28-yr TSI record in the undesirable event of a future gap in measurements. The TIM stability goal will help determine potential secular changes in solar variability.

Measurement strategy. To diagnose long-term changes in solar irradiance, TSI instruments need either

continuity with the Solar Radiation and Climate Experiment (SORCE) mission, which is flying a TIM instrument, and was originally planned to overlap with the first of the future TIMs on the National Polar-orbiting Operational Environmental Satellite System (NPOESS) (see Fig. 4).

The Glory TIM absolute accuracy is intended to be better than that of any other spaceborne TSI instrument, which will reduce the severity of a potential gap in future TSI measurements. The TIM accuracy is achieved by meticulous ground calibrations at the component level because there is currently no end-to-end calibration for TSI instruments at this level of accuracy with appropriate solar power levels. A new calibration facility, built as part of the Glory program, is intended to address the lack of such an end-to-end calibration, and will supplement the Glory TIM component-level calibrations. Comparisons between this new TSI radiometer facility and flight spares of previous TSI instruments may also help diagnose the instrument offsets shown in Fig. 3. While all instrument calibrations are done prior to launch, several are repeated or monitored on orbit.

The TIM will monitor the sun during the daytime portion of each Glory orbit. Data acquired at 50-s intervals follow changes in the TSI resulting from solar convection and oscillations, and then are averaged to provide reported daily and 6-hourly values for the TSI climate record. This fairly continual monitoring helps diagnose short-term solar mechanisms causing irradiance changes and provides sufficient sampling of the variable sun to compute an accurate

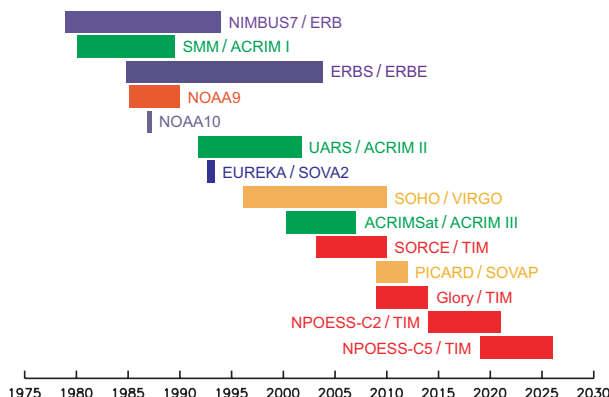


FIG. 4. TSI space missions (color coding is consistent with that in Fig. 3). Glory will maintain the TSI record between the SORCE/TIM and the future (e.g., NPOESS era) instruments.

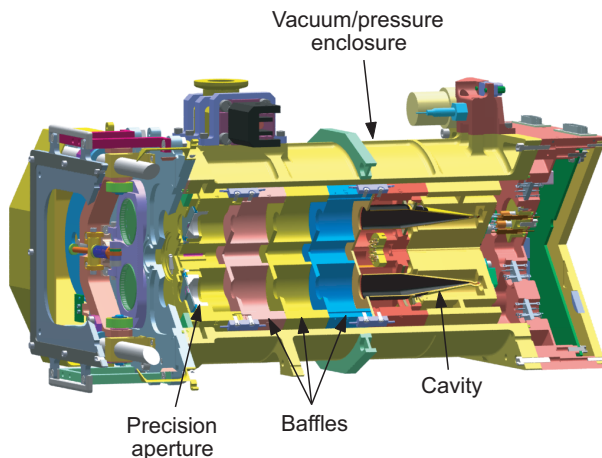


FIG. 5. TIM cutaway. Four black absorptive cavities (two shown) measure solar power passing through precision apertures in a temperature-controlled instrument.

average over each reporting period. Measurements of dark space during the eclipsed portion of each orbit correct for the TIM's internal thermal background.

TIM design. The Glory TIM, shown in Fig. 5, is the next iteration of the TIM currently flying on NASA's SORCE mission (Kopp and Lawrence 2005; Kopp et al. 2005a). This instrument is an ambient temperature, electrical substitution, null-balance solar radiometer designed to measure TSI to an absolute accuracy of 100 ppm with a noise level of < 4 ppm, which is largely achieved by a stable thermal design and by using phase-sensitive detection analysis techniques.

The TIM employs four electrical substitution cavity radiometers to measure incident sunlight power (Fig. 5). Each is located behind a National Institute of Standards and Technology (NIST)-calibrated precision aperture that determines the area over which sunlight is collected. These four radiometers provide redundancy and a means of tracking on-orbit changes in instrument sensitivity resulting from solar exposure via duty cycling. Regular comparisons between radiometers, each with different cumulative solar exposure, combined with the robust absorptive metal interior of each radiometer are what provides the TIM instrument its high degree of stability and stability tracking.

The TIM is the first spaceborne TSI instrument to use phase-sensitive detection to reduce sensitivity to noise and thermal drifts (Lawrence et al. 2003). By analyzing the data for changes exactly at and in phase with the shutter fundamental, the instrument achieves a noise level of less than 4 ppm, which is much lower than that of any other TSI instrument.

The TIM is mounted on a two-axis pointing system on the Glory spacecraft so that it can observe the sun independently of the Earth-pointed APS (Fig. 6). Closed-loop pointing control for solar tracking is provided by integrated, redundant sun sensors. An instrument digital signal processor controls the thermal balance of the TIM radiometers and shutter timing, while a dedicated microprocessor controls instrument commanding, telemetry, and pointing control.

TIM data products. Daily and 6-hourly TSI averages are produced within a week of data acquisition. These TIM data products are reported at the top of the Earth's atmosphere (for climate studies) and at 1 astronomical unit (AU) from the sun (for indicating long-term changes in the sun's output). Higher-cadence TSI values, from which these averages are computed, are useful for understanding the solar causes of the TSI variations. The TIM data products, identical to those currently being produced for the SORCE/TIM, are summarized in Table 1.

AEROSOL POLARIMETRY SENSOR. Unlike the GHGs, aerosol particles have a short lifetime in the troposphere. After they are produced they tend to mix with other agents, are transported within the troposphere both vertically and horizontally, and tend to disappear through sedimentation, rainfall cleansing, etc., within about a week (Seinfeld and Pandis 1997). Sulfate particles produced by volcanic eruptions or fossil fuel combustion reflect the solar radiation to space and thus cause atmospheric and

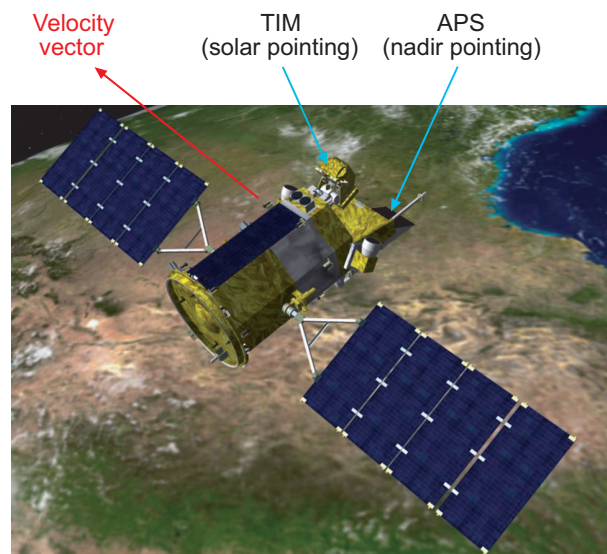


FIG. 6. The Glory spacecraft.

TABLE 1. TIM data products.

Product name	Data product	Cadence	Availability time	Data location
Level 1	Uncorrected irradiance	50 s	N/A	N/A
Level 2	Corrected irradiance at 1 AU from sun	50 s	1 week after acquisition	TIM SDPC
Level 3	Corrected irradiance at 1 AU and top of Earth's atmosphere	6-hourly and daily averages	1 week after acquisition	GSFC DAAC and TIM SDPC

surface cooling. Carbonaceous aerosols result from biomass (e.g., agricultural crop or forest) and industrial combustion. They absorb the solar radiation and reradiate it at infrared wavelengths; as such they are expected to contribute to global warming. Deposits of soot particles reduce the albedo of snow and ice surfaces and facilitate melting (Hansen and Nazarenko 2004). There are several other types of aerosols such as sea-salt particles from the ocean, mineral particles, including desert dust, and various organic particulates. Whether they cool or warm the atmosphere depends on their microphysical properties as well as their vertical location. Aerosols can also affect clouds and precipitation, and again the effect can be different for different aerosol species.

The complexity, heterogeneity, and strong variability of their global distribution make tropospheric aerosols a very difficult object of study. Because of unavoidable gaps in spatial and temporal coverage, the data collected with satellite, in situ, and ground-based instruments will never be sufficient for a direct global assessment of the long-term aerosol effect on climate. This is especially true of the aerosol indirect effect because it is almost impossible to monitor the distribution and properties of aerosols inside clouds. Therefore, the actual role of measurements in climate studies has been and will be to provide as accurate, reliable, and comprehensive a constraint on aerosol parameterizations in chemical transport and global circulation models as possible. This makes continuous satellite observations, with their quasi-global coverage and sustained, self-consistent, and uniform accuracy, an indispensable component of any systematic approach to understanding and quantifying aerosol climate impacts (Heintzenberg et al. 1996; Diner et al. 2004; Seinfeld et al. 2004).

There are two general classes of satellite instruments for aerosol and cloud remote sensing. Passive instruments measure the reflected solar or terrestrially emitted thermal radiation. Active instruments rely on an artificial source of illumination, such as a laser or transmitting antenna. Because passive and active instruments have complementary capabilities, a future comprehensive aerosol–cloud space

mission should include instruments of both types. The following discussion will be limited to passive techniques and will focus on the retrieval strategy and instrument design that allows one to maximize the information content of a passive remote sensing observation.

Measurement objectives. The left-hand panel of Fig. 7 summarizes the overall scientific objectives of a coordinated and systematic approach for dramatically improving our understanding of aerosol climate impacts and environmental interactions (Seinfeld et al. 2004). To achieve these objectives, one needs advanced models coupled with a comprehensive set of accurate constraints in the form of in situ–measured and remotely retrieved aerosol and cloud distributions and properties. As we have already mentioned, active and passive remote sensing instruments have complementary retrieval capabilities. Accordingly, the right-hand panel of Fig. 7 lists the minimal set of aerosol and cloud parameters that must be contributed by a passive satellite instrument in order to facilitate the global quantification of the direct and indirect aerosol effects on climate (Mishchenko et al. 2004).

The aerosol measurement requirements include the retrieval of the total column optical thickness (OT) and average column values of the effective radius and effective variance, the real part of the refractive index, and the single-scattering albedo (SSA). The effective radius has the dimension of length and provides a measure of the average particle size, whereas the dimensionless effective variance characterizes the width of the size distribution (Hansen and Travis 1974). Because the aerosol population is typically bimodal (e.g., Dubovik et al. 2002; Maring et al. 2003), all of these parameters must be determined for each mode. The refractive index must be determined at multiple wavelengths in a wide spectral range, for example, 400–2200 nm, because this is the only means of constraining aerosol chemical composition from space. An integral part of the retrieval procedure must be the detection of nonspherical aerosols, such as dust-like and soot particles,

because, if ignored, nonsphericity can significantly affect the results of optical thickness, refractive index, and size retrievals.

The respective minimum cloud measurement requirements include the retrieval of the column cloud OT and the average column cloud droplet size distribution as well as the determination of the cloud phase and detection of cloud particle nonsphericity.

The criteria for specifying the corresponding measurement accuracy requirements in the right-hand panel of Fig. 7 are dictated by the need to detect plausible changes of the aerosol radiative forcing estimated to be possible during the next 20 yr and to determine quantitatively the contribution of this forcing to the planetary energy balance. For example, the estimated plausible 20-yr change of the global mean aerosol OT is 0.04, whereas the global OT change required to yield a 0.25 W m^{-2} flux change is 0.01. These numbers drive the very high specified accuracy for the aerosol OT measurement, which, in turn, serves as a critical driver of the instrument design. The accuracies specified for the aerosol and cloud size distribution retrievals follow from the requirement to determine the aerosol and cloud number concentrations with an accuracy sufficient to detect and quantify the indirect aerosol effect (Schwartz and Slingo 1996). Another factor is the strong sensitivity of the droplet-nucleation efficiency to aerosol particle radius (Rosenfeld 2006). The accuracy requirement for the aerosol refractive index follows from the need to constrain the aerosol chemical composition and thereby facilitate the discrimination between natural and anthropogenic aerosol species.

APS measurement strategy. Although several satellite instruments are currently used to study aerosols and

their climatic effects on the global and regional scales (Kahn et al. 2004), the retrieval of accurate particle characteristics from space remains a very difficult task. The main cause of the problem is the extreme complexity and variability of the atmosphere–surface system and the need to characterize this system with a large number of model parameters, all of which must be retrieved simultaneously. More often than not, the requisite number of unknown model parameters exceeds the number of *independent* (i.e., complimentary in terms of their information content) measurements provided by a satellite instrument for a given scene location, thereby making the inverse problem ill posed. The retrieval procedure then yields a range of model solutions, which are all equally acceptable in that they all reproduce the measurement data equally well within the measurement errors (Mishchenko and Travis 1997a,b). The only way to ameliorate the ill-posed nature of the inverse problem is to increase the number of independent measurements per scene location until it significantly exceeds the number of unknown model parameters. Then, the retrieval procedure based on a minimization technique is likely to become stable and yield a unique solution.

The well-known methods to increase the information content of data provided by a passive instrument measuring the reflected sunlight are the following:

- to measure not only the intensity, I , but also the other Stokes parameters describing the polarization state of the reflected radiation (i.e., Q , U , and V ; Hansen and Travis 1974);
- to increase the number of spectral channels and the total spectral range covered;
- to increase the number and range of viewing directions from which a scene location is observed; and
- to improve the measurement accuracy, especially for polarization

(e.g., Mishchenko and Travis 1997a,b). In what follows, we will demonstrate that by combining the above measurement capabilities, APS affords the development of optimal passive retrieval algorithms. The latter take full advantage of the extreme sensitivity of the high-accuracy polarization data to aerosol and cloud particle microphysics, and thereby ensure the retrieval of all the quantities in the right-hand panel of Fig. 7. We will also discuss how the APS retrieval capability can be further enhanced by exploiting synergy with other passive and active satellite instruments.

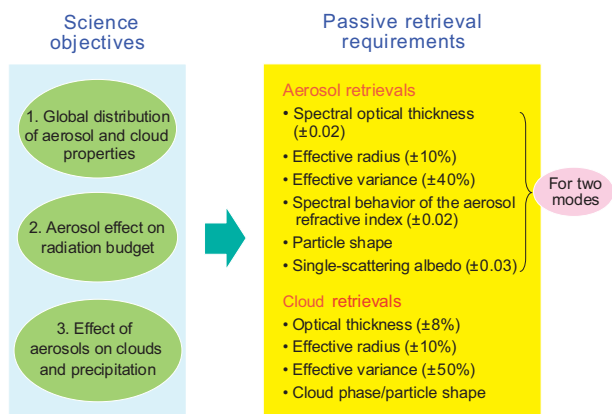


FIG. 7. Flowdown of science objectives into specific retrieval requirements for a passive aerosol–cloud satellite instrument.

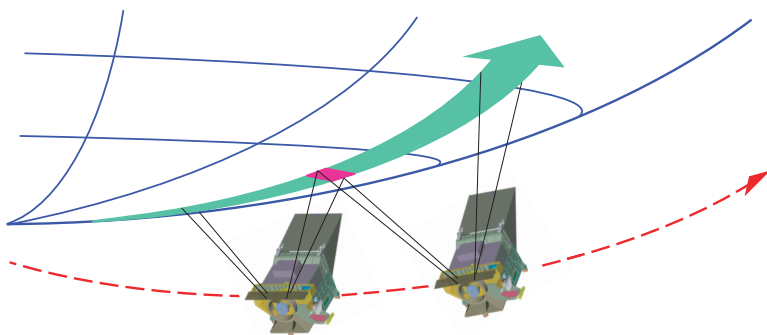


FIG. 8. Along-track multiangle APS measurements via 360° scanning from the sun-synchronous polar-orbiting Glory spacecraft.

APS design. APS is designed to offer accurate and stable along-track (Fig. 8) climate measurements over the 3 yr of nominal mission life. As discussed above, the key measurement requirements for the retrieval of aerosol and cloud properties from photopolarimetric data are *high (i.e., fine) accuracy*, a *broad spectral range*, and observations from *multiple angles*, including a method for reliable and stable *calibration* of the measurements. The APS, which is being built by Raytheon for the Glory mission, meets these measurement requirements. The APS design is based on an aircraft instrument, the Research Scanning Polarimeter (RSP; Cairns et al. 2003), which has proven the fundamental APS concept with better-than-0.2%-accuracy photopolarimetric data for a range of atmospheric conditions with a diverse range of underlying backgrounds.

The measurement approach required to ensure *high accuracy* in polarimetric observations employs Wollaston prisms to make *simultaneous* measurements of orthogonal intensity components from exactly the same scene (Travis 1992), as illustrated in Fig. 9. The field stop constrains the APS instantaneous field of view (IFOV) to 8 ± 0.4 mrad, which, at the nominal A-Train altitude (705 km), yields a geo-

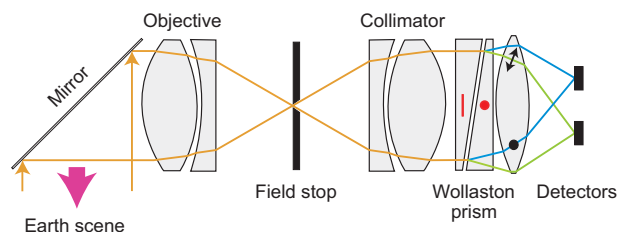


FIG. 9. RSP optical approach for polarization measurement adopted for APS. Red markings show the orientations of the optical axes of the birefringent crystals forming the Wollaston prism. Orange lines show ray paths undergoing the split into orthogonal polarizations as indicated by the green and blue lines.

metric IFOV of 5.6 km at nadir. The spatial field is defined by the relay telescope and is collimated prior to the polarization separation provided by the Wollaston prism. This method guarantees that the measured orthogonal polarization states come from the same scene at the same time and allows the required polarimetric accuracy of 0.2% to be attained. To measure the Stokes parameters that define the state of linear polarization (I , Q , and U), APS employs a pair of telescopes with one telescope

measuring I and Q and the other telescope measuring I and U , as indicated in Fig. 10 by the red “ $\times 2$ ” symbol above the three telescope icons in the block diagram. This provides a redundant measurement set that increases the reliability of APS.

The *broad spectral range* of APS is provided by dichroic beam splitters and interference filters that define nine spectral channels centered at the wavelengths $\lambda = 410, 443, 555, 670, 865, 910, 1370, 1610$, and 2200 nm, as shown in Fig. 10. Blue enhanced silicon detectors are used in the visible and near-infrared (VNIR) channels, while HgCdTe detectors, passively cooled to 160 K, are used in the shortwave infrared (SWIR) channels and offer the very high signal-to-noise ratio required to yield a polarimetric accuracy of better than 0.3% for typical clear-sky scenes over dark oceans.

All spectral channels but 1370 nm are free of strong gaseous absorption bands. The 1370-nm exception is centered at a major water vapor absorption band and is specifically intended for characterization of thin cirrus clouds. The locations of the other APS spectral channels are consistent with an optimized aerosol retrieval strategy because they take advantage of several natural circumstances, such as the darkness of the ocean at longer wavelengths in the visible and near-infrared, the lower land albedo at shorter visible wavelengths, and the potential for using the 2200-nm band to characterize the land surface contribution at visible wavelengths. The 910-nm band provides a self-contained capability to determine column water vapor amount.

The critical ability to view a scene from *multiple angles* is provided by scanning the APS IFOV along the spacecraft ground track (Fig. 8), with a rotation rate of 40.7 revolutions per minute with angular samples acquired every 8 ± 0.4 mrad, thereby yielding ~ 250 scattering angles per scene. The polarization-compensated scanner assembly includes a pair of matched mirrors operating in an orthogonal configu-

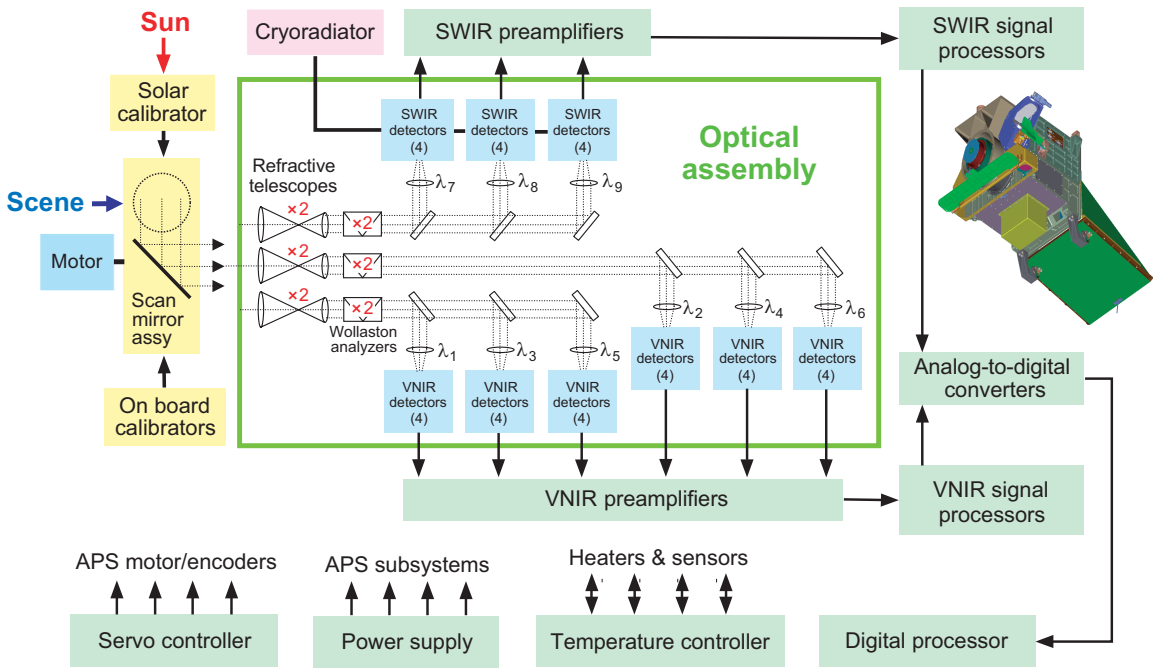


FIG. 10. APS functional diagram shows architecture, principal assemblies, and signal flow.

ration and has been demonstrated to yield instrumental polarization less than 0.05%. From the nominal A-Train altitude, the APS viewing angle range at the Earth is +60°/−80° with respect to nadir.

The scanner assembly also allows a set of *calibrators* to be viewed on the side of the scan rotation opposite to the Earth (Fig. 10). The APS onboard references provide comprehensive tracking of polarimetric calibration throughout each orbit, while radiometric stability is tracked monthly to ensure that the aerosol and cloud retrieval products are stable over the period of the mission.

APS science products. A detailed listing of the APS level-3 science products along with the expected uncertainties is given in Mishchenko et al. (2004). A brief summary is provided in Table 2. All products will be delivered with a ~6 km spatial resolution (at nadir) along the Glory ground track. The nominal A-Train

orbit implies a repeat cycle of 233 revolutions every 16 days. The initial level-3 results will be available no later than 6 months after launch; further data will be generated at a keep-up rate and made available through the Goddard Space Flight Center Distributed Active Archive Center (GSFC DAAC).

TABLE 2. APS level-3 aerosol and cloud data products.

Data product	Range	Uncertainty
Column spectral* aerosol optical thickness (fine and coarse modes)	0–5	0.02 over ocean, 0.04 over land
Aerosol effective radius (fine and coarse modes)	0.05–5 μm	10%
Effective variance of aerosol size distribution (fine and coarse modes)	0–3	40%
Aerosol spectral* real refractive index (fine and coarse modes)	1.3–1.7	0.02
Aerosol spectral* single-scattering albedo (fine and coarse modes)	0–1	0.03
Aerosol morphology (fine and coarse modes)	Spherical aerosols, irregular dust particles, soot clusters	N/A
Cloud thermodynamic phase	Liquid, mixed, ice	N/A
Liquid cloud column optical thickness	0–300	8%
Cloud droplet effective radius	1–50 μm	10%
Effective variance of cloud droplet size distribution	0–2	50%

*At least in three spectral channels.

As with any satellite instrument, the nonzero size of the APS IFOV will cause partial cloud contamination of many APS pixels. Our initial plan to address this problem uses two simple high-spatial-resolution cloud cameras (CCs) in combination with a cloud-screening algorithm, similar to that developed for the Moderate-Resolution Imaging Spectroradiometer (MODIS) by Martins et al. (2002). However, disposing of cloud-contaminated pixels may not be the best strategy in a study of the aerosol indirect effect, because these are the pixels where the various aerosol–cloud interactions occur. Therefore, we plan to pursue alternative approaches, such as to attempt the retrieval of both the cloud and the dominant aerosol mode within a partially cloudy pixel and to exploit the fact that Q and U become insensitive to subpixel cloudiness at scattering angles $\leq 140^\circ$.

Because APS shares many design features with RSP, the latter can be expected to provide a close model of the future APS performance. Numerous RSP retrievals have been validated and described by Chowdhary et al. (2001, 2002, 2005). Examples of the fidelity of the aerosol OT, size distribution, and absorption estimated from the APS type of remote sensing measurement during seven different flights are shown in Fig. 11. In Fig. 11a we see that the spectral OT values retrieved from polarimetric measurements agree well with those measured by ground-based sunphotometers over an OT range from 0.05 to more than 1. The absence of spectrally dependent biases in these retrievals also demonstrates the reliability of the size distribution estimate for both small and large modes of a bimodal aerosol distribution.

Comparisons have also been made between in situ and retrieved size distributions and have also been found to agree extremely well (difference in aerosol effective radius of less than $0.04\ \mu\text{m}$).

The aerosol SSA can also be estimated from polarimetric measurements because of the differing sensitivities of polarized and unpolarized reflectances to aerosol absorption. In Fig. 11b (Chowdhary et al. 2005), the SSA derived from polarimetry is compared with in situ (Magi et al. 2005) and ground-based sky radiance (Dubovik et al. 2002) estimates. The discrepancy between these estimates may be related to the loss of particles in the sampling system for in situ measurements, humidification of the in situ extinction (but not the absorption) coefficients, and uncertainties in the SSA retrieval from Aerosol Robotic Network (AERONET) data that may be caused by horizontal variability in the aerosol burden. Nonetheless the polarimetric estimate of SSA is consistent with the other measurements given their inherent uncertainties. Overall, Fig. 11b illustrates the complexity of retrieving SSA from both in situ and remote sensing measurements and suggests that the validation of SSA retrievals from APS data will be a challenging task.

Existing methods for remotely determining the size of cloud particles use the fact that the efficiency of liquid and ice absorption depends on particle size (Nakajima and King 1990), or that the rainbow and glory features of radiation scattered by water droplets are sensitive to particle size (Bréon and Goloub 1998). APS will make measurements that allow both methods to be combined, thereby reducing their

individual limitations. Polarized reflectances are sensitive to the droplet size distribution (both effective radius and effective variance) in the top layer (optical depths less than three), while the radiance in spectral bands where ice and water are absorbing (1600 and 2200 nm) is sensitive to a weighted integral through the depth of the cloud (Platnick 2000). The type of measurements made by APS therefore requires a cloud model with two vertical layers. This allows the complete set of measurements to be matched, with

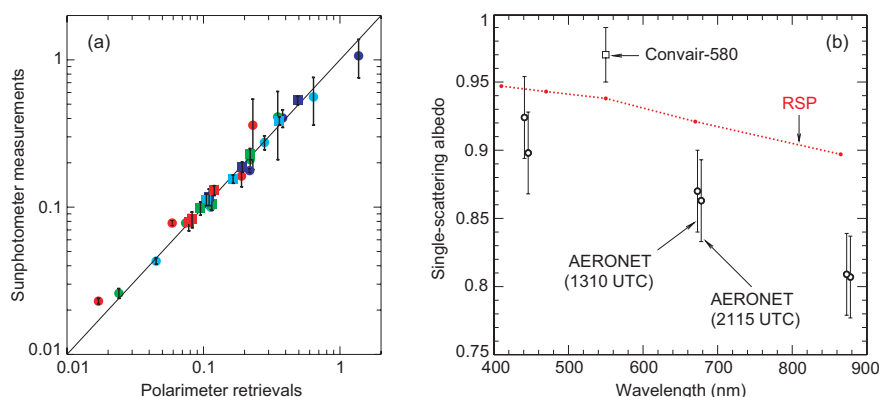


FIG. 11. (a) Optical thickness comparison. Sunphotometer measurements at 410/443 (blue), 500 (turquoise), 673 (green), and 865 (red) nm are compared with RSP retrievals for the same wavelength. The circular symbols are for retrievals over land while the square symbols are for retrievals over ocean. Error bars are only shown for the sunphotometer measurements. (b) Single-scattering albedos as a function of wavelength. The red dotted line shows the best-estimate values retrieved from RSP data. Also included are estimates from data collected during Convair-580 flight 1874 and from the AERONET data.

the additional benefit of providing sensitivity to the vertical profile of droplet size and consequently reducing any biases in the estimated liquid water path and droplet number density. In addition, the polarized reflectance at scattering angles well separated from the rainbow and glory can be used to determine cloud-top height (Goloub et al. 1994) and the properties of haze above the cloud top.

A good illustration of the performance of the RSP cloud algorithm is provided by a comparison of the retrieved properties at cloud top with two sets of in situ measurements obtained during the Coastal Stratocumulus Imposed Perturbation Experiment. The RSP retrievals were compared with in situ estimates using a forward-scattering spectrometer probe on 22 July 2003 giving, respectively, 7.8 (0.8) and 8.7 (0.7) μm for effective radius and 0.04 (0.02) and 0.07 (0.015) for effective variance, where the parenthetic figures are the sampling uncertainty, and the retrieved cloud OT was 14.0. On 25 July 2003 the comparison of remote sensing retrievals with in situ estimates gave 9.4 (1.4) and 9.3 (1.4) μm for effective radius and 0.152 (0.072) and 0.176 (0.037) for effective variance, and the retrieved OT was 7.3. The OT retrievals were within 0.1 of the in situ estimates on both days, although this agreement is probably fortuitous given that the sampling variability in the optical thickness was $\sim 10\%$ on both days and the remote sensing measurements were not perfectly aligned with the in situ observations. Nonetheless, the retrieved sizes are in good agreement with the in situ measurements in terms of both effective radius and effective variance for both wide (July 25) and narrow (July 22) size distributions. It is also interesting to note the factor-of-3 change in effective variance between these 2 days.

Synergy with models, ground-based networks, and A-Train instruments. The unique APS design is intended to maximize the microphysical retrieval capability of the instrument. Because of this strategy, APS is not an imager and provides no cross-track coverage beyond the width of its nominal IFOV. The rich history of polarimetry suggests that it would be very hard to design an imaging polarimeter with the instrument characteristics (in terms of the spectral range and number of spectral channels, range and number of viewing directions, and polarization accuracy), and, thus, the retrieval potential comparable to those of APS. However, the inherent lack of cross-track coverage in APS observations should be recognized as a limitation.

The trade-off between imaging with a greatly reduced retrieval capability and the detailed infor-

mation from precise along-track polarimetry was analyzed during the early stages of the APS design. It was demonstrated by Rossow (1993) that in addition to optimizing aerosol and cloud microphysical retrievals, the APS along-track measurement strategy provides sufficient global sampling for long-term climate studies. This is especially true if, as intended, the APS data products are assimilated into advanced models (e.g., Ackerman et al. 2004; Seinfeld et al. 2004; Ginoux et al. 2006). In this regard, APS data can be considered as a comprehensive constraint on models that supplements and greatly extends that provided by AERONET (Holben et al. 1998) and other ground networks, especially over the oceans.

Although APS, in combination with the CCs, is a self-sufficient instrument with respect to the science product objectives summarized in Table 2, its utility can be enhanced by exploiting the synergy with other space instruments. Because Glory is expected to fly as part of the A-Train (Fig. 2), APS can contribute greatly to the A-Train strategy to quantify the aerosol forcing of climate proposed recently by Anderson et al. (2005). The largest uncertainty in the MODIS (Tanré et al. 1997) and Polarization and Directionality of the Earth's Reflectance (POLDER) instrument (Deschamps et al. 1994) retrievals is that many model assumptions are poorly constrained. By providing real-time aerosol characteristics along the ground track, APS can be expected to reduce the uncertainty and widen the swath of improved aerosol retrievals from ~ 6 to perhaps ~ 100 km and thereby meet the limited operational as well as climate change needs.

Another example of APS–MODIS synergy could be improved retrievals of the aerosol SSA using the so-called sunglint technique. Specifically, the APS measurements collected off sunglint can be used to constrain the scattering component of OT, whereas the MODIS radiance measurements in the glint can be used to estimate the absorption component of OT (Kaufman et al. 2002).

Perhaps the most exciting example of synergy would be combined aerosol and cloud retrievals using data from APS, the Cloud–Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) lidar (Poole et al. 2003), and the CloudSat radar (Stephens et al. 2002), provided that the latter instruments are still active at the time of the Glory launch. The APS measurements have limited sensitivity to the vertical distribution of aerosols and liquid clouds, whereas the active instruments are limited in their ability to retrieve the aerosol and cloud OT and microphysical properties. However, a combined retrieval algorithm employing the APS photopolarimetric data and the

lidar and radar backscatter data can be expected to yield the vertical distribution of the aerosol and cloud microphysics and optical depth with unprecedented accuracy.

Validation of APS products. Validation of APS retrievals will be challenging for two reasons. First, the expected accuracy of APS retrievals of aerosol and cloud particle microphysical properties is unlikely to be matched by most ground-based and in situ instruments. An ideal in situ instrument to verify the APS microphysical retrievals would be a high-accuracy airborne polarization nephelometer performing measurements at several widely separated wavelengths and over the entire range of scattering angles, but such an instrument has yet to be fielded.

Second, the lack of cross-track coverage will make the collocation of APS measurements with those collected from the ground or from aircraft problematic. It is, therefore, desirable to have ground network locations positioned very close to the APS ground track and to schedule collocated underflights of APS by aircraft equipped with suitable in situ and remote sensing instrumentation, including RSP.

The availability of RSP justifies an ongoing effort preceding the APS launch, in which RSP is used for low-cost flights on small survey aircraft to acquire observations of specific aerosol types, preferably over existing ground network locations. Obtaining data from high altitudes over a wide range of conditions will be necessary to address the issue of simultaneous retrievals of aerosols and thin cirrus. This calls for a separate plan for field campaigns,

using RSP on high-altitude aircraft such as Proteus. The expectation is that such campaigns would be organized with other instruments to defray costs and generate broader applications. The main benefit of participating in large-scale field campaigns (e.g., Russell and Heintzenberg 2000; Reid and Maring 2003), including those in the framework of existing calibration/validation plans for other satellite instruments, is the cross validation of retrievals from different ground-based, aircraft, and satellite instruments. In particular, the validation of water and ice cloud microphysical retrievals requires in situ aircraft measurements.

THE MISSION. Figure 12 shows the overall organization of the Glory mission. Glory will be launched from the Vandenberg Air Force Base (VAFB) aboard a Taurus 3110 launch vehicle and will be flown in a nominal 705-km-altitude and 98.2°-inclination ascending sun-synchronous orbit with a 1334 LST equatorial crossing time. The Glory launch is scheduled for December of 2008 with a nominal 3-yr mission lifetime.

The Glory bus (Fig. 6) is three-axis stabilized with deployable, articulating solar panels, multiple computers, and X- and S-band radio frequency communication capabilities. The Glory spacecraft will be operated from the Mission Operations Center (MOC) at the Orbital Sciences Corporation campus in Dulles, Virginia, via the NASA Internet Protocol Operational Network (IONet). The ground communications will use the Universal Space Network site in Poker Flat, Alaska, as the primary contact station.

The APS/CC Science Data Processing Center (SDPC) at the Goddard Institute for Space Studies (GISS; New York City, New York) will be responsible for scheduling the APS and CC instrument activities, monitoring the instrument performance, and generating aerosol and cloud data products. The TIM SDPC at the Laboratory for Atmospheric and Space Physics (LASP; University of Colorado, Boulder) will provide the capability to command the TIM instrument, monitor its performance, and generate TSI

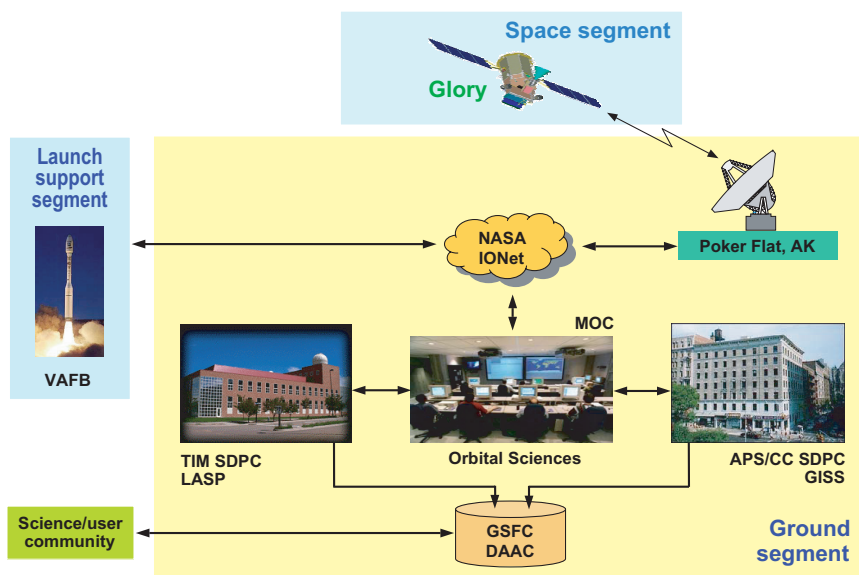


FIG. 12. The Glory mission overview.

science data products. The APS and TSI data products will be archived and distributed by the GSFC DAAC. The TIM data will also be available from the TIM SDPC.

SUMMARY. Glory is an Earth-orbiting observatory designed to continue and improve upon long-term monitoring of two key forcings influencing global climate. One of its primary objectives is to determine the global distribution of aerosol and cloud properties with very high accuracy, and thereby facilitate the quantification of the aerosol direct and indirect effects on climate. The other is to continue the 28-yr TSI measurement record needed to quantify the effect of solar variability on the Earth's climate.

These objectives are met by implementing two separate science instruments. The APS has the ability to collect multiangle, multispectral photopolarimetric measurements of the atmosphere and the underlying surface along the satellite ground track. APS observations will provide accurate retrievals of aerosol and cloud microphysical parameters and are expected to improve global aerosol assessments with other A-Train instruments. They will also pave the way for future operational results by providing a proof of concept and risk reduction and demonstrating synergy with other passive and active instruments.

The TIM will measure sunlight incident on the Earth's atmosphere by collecting high-accuracy and -precision TSI data. The Glory TIM is an improved version of the TIM currently flying on SORCE, and so will maintain continuity of the multidecadal benchmark TSI record. Improvements in absolute accuracy reduce the risk to this record in the event of a potential future gap in TSI measurements.

At present, the Glory science team consists of several researchers responsible for the development of retrieval algorithms and data processing and storage software, as well as members of an advisory committee representing various aspects of the Glory science. It is planned that near the time of launch the Glory project will support a larger team and will include full-scale research efforts aimed at improving, validating, and assimilating the Glory data products and using them in climate studies.

The scientific knowledge provided by the Glory mission will be essential to understanding climate change for sound, scientifically based economic and policy decisions related to environmental changes caused by climate variability. Subsequent launches of both Glory instruments would serve to continue their benefits to climate trend assessments well beyond the initial Glory mission demonstration.

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